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Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR



## Executive summary

# Hot-stream in-situ acoustic impedance measurements on various air-filled cavity and porous liners



*Instrumented annular liner test cell*

### Problem area

Research is needed to develop innovative concepts to reduce aircraft engine noise at source. Aerospace industry is seeking for alternatives for conventional perforate acoustic liners such as new linear and porous liners to suppress turbofan engine exhaust noise. Before these liners can be evaluated, down-selected and tested in real engines, it is useful and cost effective to determine the acoustic liner properties, i.e. the insertion loss and the acoustic impedance, under simulated hot engine operating conditions in a suitable test rig, in this study the NLR hot stream acoustic liner test facility. The paper will briefly describe the facility and measurement techniques and will mainly focus on the results of hot stream liner testing on various types of liners, i.e. air-filled SDOF-cavity liner (Single Degree Of Freedom) with a

perforated and linear facing sheet and porous liners. This work has been carried out in the European Growth project GRD1-2000-25297 "SILENCE(R)".

### Description of work

In-situ acoustic impedance measurements on various types of liners (perforate, linear and porous) under grazing flow were carried out in the NLR hot stream acoustic liner test facility. The test matrix covered 6 engine operating conditions. The maximum test temperature is dependent on flow Mach number (500 °C at a flow Mach number of 0.35 or 440 °C at a flow Mach number of 0.4). Maximum overall sound pressure level (SPL) is 142 dB.

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### Author(s)

E.R. Rademaker  
H.M.M. van der Wal  
E.G.M. Geurts

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**Results and conclusions**

The tests reveal a clear distinction between the perforate type of liner and the linear type:

1. the perforate type has a resistance, which is strongly dependent on grazing flow Mach number and SPL and is nearly independent on temperature and
2. the linear type has a resistance, which is nearly independent on grazing flow Mach number and SPL and is strongly dependent on temperature.

Furthermore the acoustic parameters of the porous liners were found to be strongly dependent on temperature.

**Applicability**

The facility and measurement techniques have proven to be useful for the selection of liner candidates for the hot section(s) of aero-engines. Optimal acoustic treatment for these hot areas will mainly reduce high frequency turbine noise and to a lesser extend low frequency noise generated in the combustion chamber.



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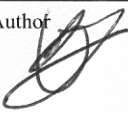

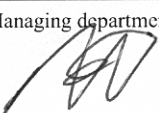
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# **The Sixteenth International Congress on Sound and Vibration**

## **Kraków, 5-9 July 2009**

### **HOT-STREAM IN-SITU ACOUSTIC IMPEDANCE MEASUREMENTS ON VARIOUS AIR-FILLED CAVITY AND POROUS LINERS**

Edward R. Rademaker, Henk M.M. van der Wal and Evert. G.M. Geurts

*National Aerospace Laboratory NLR, Voorsterweg 31, 8316 PR Marknesse, the Netherlands, e-mail: [radema@nlr.nl](mailto:radema@nlr.nl), [vdwal@nlr.nl](mailto:vdwal@nlr.nl) and [geurts@nlr.nl](mailto:geurts@nlr.nl)*

In-situ acoustic impedance measurements on various types of liners used in hot areas of aeroengines were successfully carried out in the new NLR hot stream acoustic liner test facility. Characteristic results of three liners, i.e. one of the perforate, linear and porous type, are discussed in this paper. Liner experiments were carried out at six test conditions, varying from ambient temperature and no flow to a maximum temperature of 500 °C and a flow Mach number of 0.35 or a maximum flow Mach number of 0.4 and a temperature of 440 °C. The tests reveal a clear distinction between the acoustic properties of the perforate type of liner and the linear type:

(1) the perforate type has a resistance, which is strongly dependent on grazing flow Mach number and SPL and is nearly independent of temperature and

(2) the linear type has a resistance, which is nearly independent of grazing flow Mach number and SPL and is strongly dependent on temperature.

Tests on a ceramic porous liner reveal that the propagation constant and the characteristic impedance are strongly dependent on temperature.

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## 1 Introduction

Conventional perforate acoustic liners are presently used in hot areas of aero-engines. Current linear screen-on-perforate liners (“cold stream”) do not meet the thermal and functional requirements valid for engine exhaust areas (“hot stream”= typically 700 °C). Aerospace industry is seeking for alternatives for conventional perforate acoustic liners such as new linear and porous liners to investigate means to further suppress turbofan engine exhaust noise. Before these liners can be evaluated, down-selected and finally tested in real engines, it is useful and costs effective to determine the acoustic liner properties, i.e. the insertion loss and the acoustic impedance, under simulated engine operating conditions in a suitable test rig, in this study the new NLR hot stream acoustic liner test facility. This paper will briefly describe the facility and the in-situ acoustic impedance measurement technique and will mainly focus on the results of hot stream testing on various types of liners, i.e. air-filled SDOF-cavity liners with a perforated or linear facing sheet (Single Degree Of Freedom) and porous liners. SDOF-liners have a single row of honeycomb cavities contrary to MDOF-liners (Multiple Degree of Freedom), which consist of several rows honeycomb cells separated by so-called septa.

## 2 Experimental set-up

### 2.1 Test facility

Test rig is the hot stream liner test facility (Figs 1 and 2, see also Ref. 1). It consists of a compressor, combustion or gas burning chamber, a contraction, a rectangular flow duct of 1.2 m length with exit nozzle and cross section dimensions of 0.15 x 0.05 m<sup>2</sup>. The maximum compressor capacity is about 3000 m<sup>3</sup> /h, whereas maximum burner capacity is 500,000 kcal/h. The hot gases of the free jet are flowing into a collector, with an inlet diameter of 1.2 m and further outwards to an exhaust system. The modular flow duct elements are: a source section of 300 mm length, a liner test section with two boxes (400 mm), two acoustic and aerodynamic measurement sections upstream and downstream of the liner test section (2 x 140 mm) and an exit nozzle (100 mm). The rig is made of stainless steel plates of 3 mm thickness welded together. The elements are connected by flanges of 10 mm thickness. Loudspeakers are connected to the source section by two double wall air-cooled horns. The liner test panels for in-situ acoustic impedance measurements are placed at the side-wall of the source section opposite to the horns. The acoustic test panels for insertion loss measurements (300 x 170 mm<sup>2</sup>) can be placed in the boxes of the liner test section. Note that results of this type of testing are not the subject of this paper and are therefore not further discussed. In-situ acoustic impedance (and insertion loss) measurements on test samples can be carried out in the frequency range between 1.0 and 6.0 kHz at an overall SPL of 142 dB up to:

1. a maximum temperature of 500 °C at a flow Mach number of 0.35 or
2. a maximum flow Mach number of 0.4 at a temperature of 440 °C.

### 2.2 Measurement technique

In-situ acoustic impedance measurements are carried out on an annular test cell of 12 mm hub and 42 mm outer diameter and cell depth of 14 mm, see fig. 3). Details of the measurement technique to determine the normalized specific acoustic impedance  $Z$  defined by  $Z = \frac{P}{\rho c v}$  (1) are given in Ref. 2 ( $p$  and  $v$  are the Fourier transformed acoustic pressure and velocity,  $\rho$  the mean density and  $c$  the speed of sound).

The test cell, located opposite to the horns of the source section, is instrumented with five (cold) or three (hot) water-cooled Kulite WCT-312 pressure transducers (1 at the facing sheet and 2 or 4 at the back wall). The temperature is measured with 1 (cold) or 3 thermocouples (hot). The measurement technique reveals the acoustic impedance of the tested facing sheet or the cavity impedance, the characteristic impedance and propagation constant of the tested porous material. The maximum valid frequency is dependent on the on-set of higher order modes in the annular test cell and therefore dependent on temperature ( $f_{\max} = 3.5$  kHz at 20 °C and 5 kHz at 500 °C). Note that for the porous type of liners usually three measurements are required: empty cavity with facing sheet, cavity half filled with porous material and facing sheet and cavity fully filled with porous material and facing sheet. The porous material is characterised by the propagation constant  $\mu$  and the characteristic impedance  $Z_c$ . The acoustic pressure  $p$  for a plane wave propagating in positive  $x$ -direction in a stiff porous material and the characteristic impedance (the ratio of the pressure  $p$  and the acoustic velocity  $v$ ) are given by respectively

$$p = p_0 e^{i(-\mu x + \omega t)} \quad (2) \quad \text{and} \quad Z_c = \frac{p}{v} = \frac{\lambda}{i\mu} \quad (3)$$

### 2.3 Tested liners

Various facing sheets of the perforate and linear type were brazed upon the test cell. The results of one of each liner type will be discussed in this paper. Parameters of the facing sheet geometry are given in table 1. Three configurations with the cavity partly or fully filled with porous liner material were tested. The results obtained from the ceramic porous material provided by SENER and INASMET will be discussed here (see table 1).

### 2.4 Test matrix

The in-situ acoustic impedance has been determined at 6 nominal operating conditions (see table 2 with nominal and actual values). The listed temperatures are nominal and actual total temperatures. The surface and liner cavity temperatures at maximum nominal temperature of 500 °C may be respectively 50 °C to 100 °C lower than the total temperature in the duct, at minimum temperature of 200 °C, 30 °C to 60 °C lower. The actual Mach numbers are also somewhat lower than the nominal values. Various types of acoustic excitation at each operating condition were applied: broadband periodic excitation, broadband random excitation and tonal excitation (the first two at maximum excitation level and the latter at 120 and 140 dB). Note that liner tests without grazing flow can only be done at ambient temperature and that the nominal values are used in the sequel for discussion.

### 2.5 Data acquisition

Acoustic and aerodynamic data were acquired with the multi-channel GBM-system (Ref. 3). Data-acquisition parameters are dependent on type of acoustic excitation (Table 3). Aerodynamic data consist of static pressure data along the duct, 4 total pressure rakes to determine the flow velocity profiles and various temperatures: total and surface temperatures in the duct and liner temperature.

## 3 Experimental results

Commissioning of the rig and liner tests lasted for about a six months period. After commissioning, initial broadband results were obtained under periodic broadband excitation. It seemed however that acoustic excitation by random broadband noise unexpectedly gives much better results (see fig. 4, where the impedance of the annular test cell covered with the perforated plate of 10% porosity is given at both excitations). The broadband results shown in the sequel therefore are obtained using broadband random excitation. The source spectrum at the latter excitation is shown in figure 5 at a flow temperature of 500 °C and flow Mach number of 0.35. The frequency resolution is 20.0 Hz and the overall sound pressure level is 135 dB. Note that the overall sound pressure level is dependent on

temperature and Mach number and higher at lower values of these operating conditions (142 dB at  $T = 20\text{ }^{\circ}\text{C}$  and  $M = 0.0$ ). Acoustic signal to flow noise ratio as measured on the liner surface is better than 10 dB for frequencies within the range between 1.0 and 3.0 kHz (see fig. 5 for  $T = 500\text{ }^{\circ}\text{C}$  and  $M = 0.35$ ).

### 3.1 Liner of the perforate type

The results of the locally-reacting liners in the sequel are presented as the normalized specific facing sheet impedance  $Z_f$  defined as  $Z_f = R_f + iX_f = R_f + imk$  (4) with  $R_f$  the facing sheet resistance,  $m$  the so-called mass reactance and  $k$  the acoustic wave number. The resistance  $R_f$  and reactance of the  $X_f$  perforated facing sheet (denoted by  $R$  and  $X$ ) are shown in figure 6 as a function of frequency at four rig operating conditions. The results are obtained using broadband random (lines) and single tone excitation (symbols) at a maximum SPL of 140 dB. At ambient temperature, the well-known non-linear properties are confirmed here (see also Ref. 4):

1. grazing flow causes the resistance to increase significantly (from a value of 0.1 at no-flow condition and 0.75 at  $M = 0.35$  for frequencies in the range from 1 to 2 kHz) and
2. the mass reactance reduces by a factor of about 2 compared to the no-flow condition.

In the presence of grazing flow of equal Mach number ( $M = 0.35$ ), the facing sheet resistance seems to be nearly independent of temperature. The mass reactance at this grazing flow Mach however decreases further to half its value when the temperature is increased from  $20\text{ }^{\circ}\text{C}$  to  $500\text{ }^{\circ}\text{C}$ . Note the good agreement between the results obtained from acoustic broadband random and tonal excitations.

### 3.2 Liner of the linear type

The results on the Felt metal linear facing sheet under broadband random and tonal excitation a maximum SPL of 140 dB are shown in figure 7. The presence of grazing flow at ambient temperature surprisingly causes the resistance to decrease 14 percent, while normally an increase of about the same amount would be expected. The mass reactance remains nearly constant. A rise of the temperature from  $20\text{ }^{\circ}\text{C}$  to  $500\text{ }^{\circ}\text{C}$  at  $M = 0.35$  results into an increase in the facing sheet resistance of a factor 1.5 (from 1.2 to 1.8). Measurements on other linear liners also show this effect, although the multiplication factor may be somewhat higher (between 1.5 and 2.0). The mass reactance  $m$  derived from the slope of the reactance  $X_f = mk$  with  $k$  the wave number) and averaged over a period of the fluctuation seems to decrease 30% when the temperature rises from  $20\text{ }^{\circ}\text{C}$  to  $500\text{ }^{\circ}\text{C}$  ( $m$  decreases from a value of 10 mm to a value of 7 mm). The cause of the sinusoidal fluctuation in measured resistance and reactance is not known for sure (it might be caused by a partly detached vibrating flow guiding plate in the source section, which has been repaired at a late stage of the test campaign).

### 3.3 Porous liner

As stated earlier, three measurements are necessary to determine the characteristic acoustic parameters for the porous material and the liner acoustic impedance (empty cavity covered with facing sheet, cavity half and fully filled with porous material and covered by facing sheet). The in-situ acoustic impedance of the liner half filled with porous ceramic material as intermediate result is shown in figure 8 at a flow Mach number of 0.35 at two temperatures ( $20\text{ }^{\circ}\text{C}$  and  $500\text{ }^{\circ}\text{C}$ ). The resistance at a frequency of 1500 Hz increases from a value of about 1.6 at low temperature to a value of about 1.8 at high temperature. The reactance at this frequency decreases from a value of  $-0.6$  to  $-1.5$ .



The measured values of the propagation constant  $\mu$  and characteristic impedance  $\lambda$  of the porous material at four temperatures ( $T = 20, 200, 440$  and  $500$  °C) and two Mach numbers ( $M = 0.0$  and  $0.35$ ) are shown in figure 9. The real part of  $\mu$  relates to the phase velocity, the imaginary part to the damping. The real part and imaginary part of  $\lambda$  relate to the magnitude of the acoustic volume velocity and the phase difference between the acoustic pressure and the volume velocity. Both parameters  $\mu$  and  $\lambda$  are linear functions of frequency. The following results by increasing the temperature from  $20$  °C to  $500$  °C are found: (i) the real part of  $\mu$  decreases with 20 percent, (ii) the imaginary part of  $\mu$  remains nearly constant, (iii) the real part of  $\lambda$  reduces on average with 40% and (iiii) the imaginary part of  $\lambda$  reduces to half of its value.

## 4 Conclusions

In-situ acoustic impedance measurements on various types of liners were successfully carried out in the new NLR hot stream liner test facility. The tests reveal as main result a clear distinction between the perforate type of liner and the linear type as partly (minus the well known non-linear flow effect) is illustrated in figure 10:

1. the perforate type has a resistance, which is strongly dependent on grazing flow Mach number and SPL and is nearly independent on temperature and
2. the linear type has a resistance, which is nearly independent on grazing flow Mach number and SPL and is strongly dependent on temperature.

The acoustic parameters of various porous liners were determined and were found to be strongly dependent on temperature. This study was carried out in the European Growth project GRD1-2000-25297 "SILENCE(R)". The author would like to thank SNECMA, Turbomeca, SENER and INASMET for their willingness to release experimental results.

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## Tables

**Table 1 Tested liners**

Number	Liner type	Parameters
1	Perforate	Thickness 0.8 mm, hole diameter 1.5 mm and 10% porosity
2	Linear	Felt metal, thickness 0.9 mm, $R \approx 1.0$
3	Porous	Ceramic material, 14% open porosity covered by a perforate plate of 40% porosity

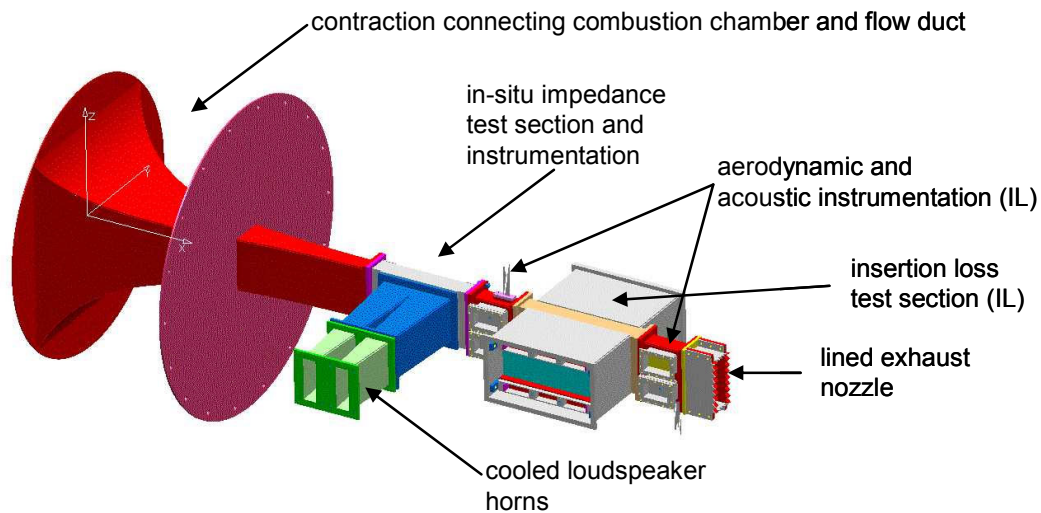
**Table 2 Test matrix with nominal and actual values**

Broadband periodic (max. dB), broadband random (max dB) and tonal (1.0 (0.5) 5 kHz) excitation (120 and 140 dB), nominal values					
T = 20 °C, M = 0.0	T = 20 °C, M = 0.35	T = 200 °C, M = 0.35	T = 440 °C, M = 0.3	T = 440 °C, M = 0.4	T = 500 °C, M = 0.35
Corresponding actual values					
T = 20 °C, M = 0.0	T = 20 °C, M = 0.33	T = 210 °C, M = 0.33	T = 460 °C, M = 0.285	T = 460 °C, M = 0.36	T = 520 °C, M = 0.325

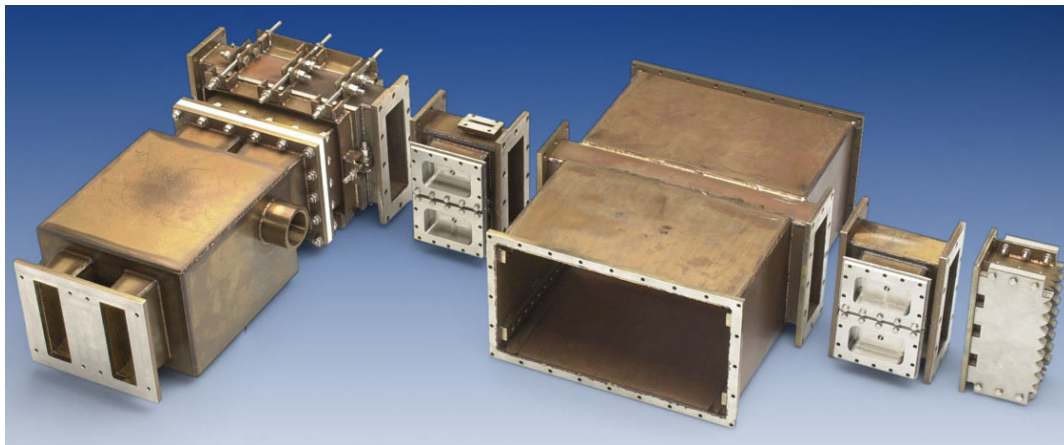
**Table 3 Data-acquisition and processing parameters**

Parameter	Broadband random/period excitation	Tonal excitation
Sampling frequency	20.48 kHz	20.48 kHz
Filter	Band pass: high pass A-weighting (- 3 dB at 0.5 kHz) and anti-aliasing (110.0 kHz)	Low pass anti-aliasing (110.0 kHz)
Measuring time	8 s.	8 s.
Frequency resolution	20.0 Hz	5.0 Hz

## Figures



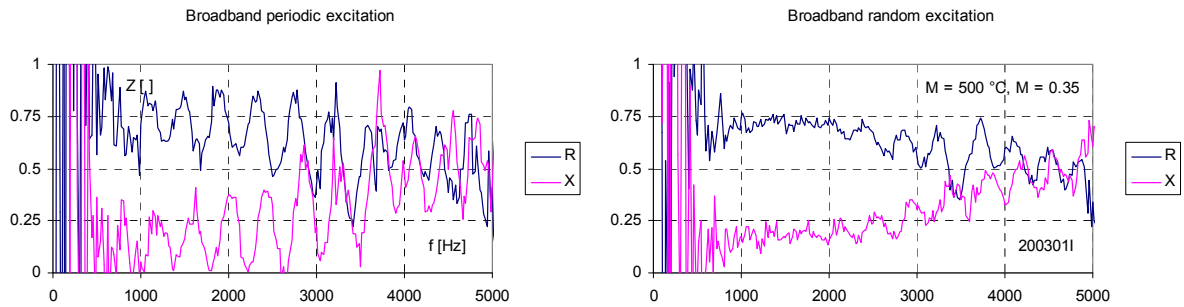
**Figure 1** The NLR hot stream acoustic liner test facility



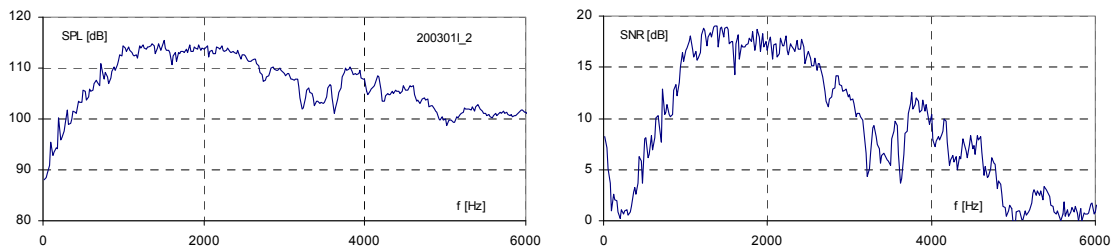
**Figure 2** Photograph of the modular flow duct elements of the facility



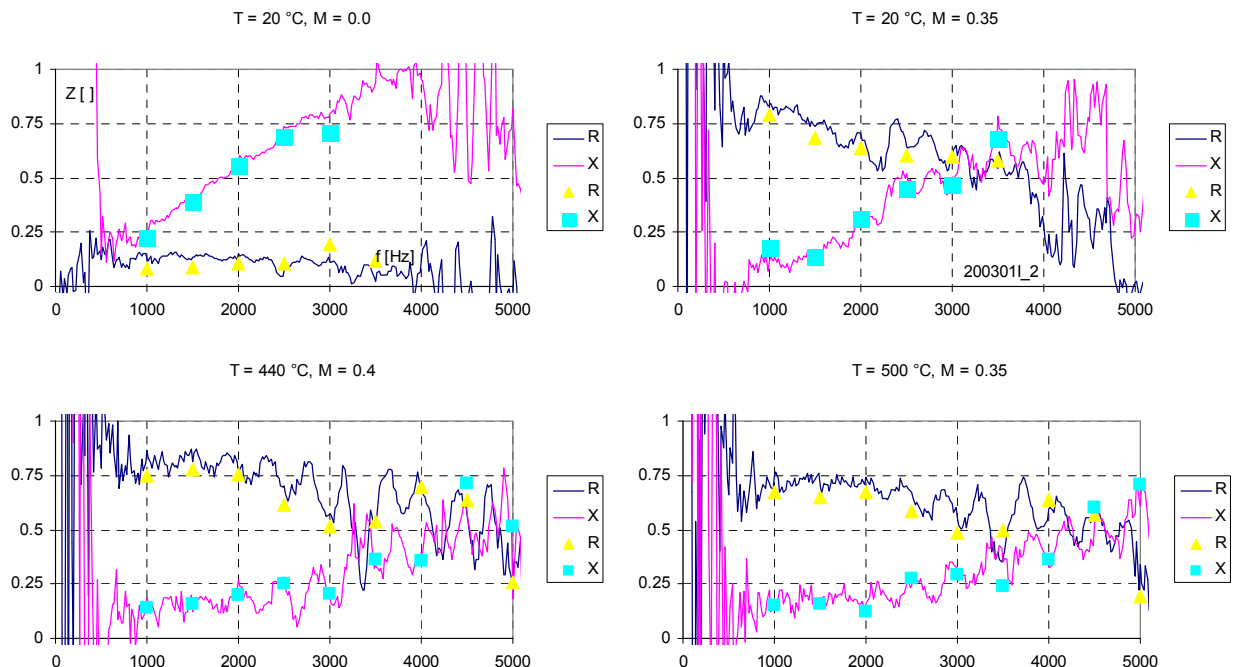
**Figure 3** Annular test cell instrumented with Kulite WCT-312 pressure transducers



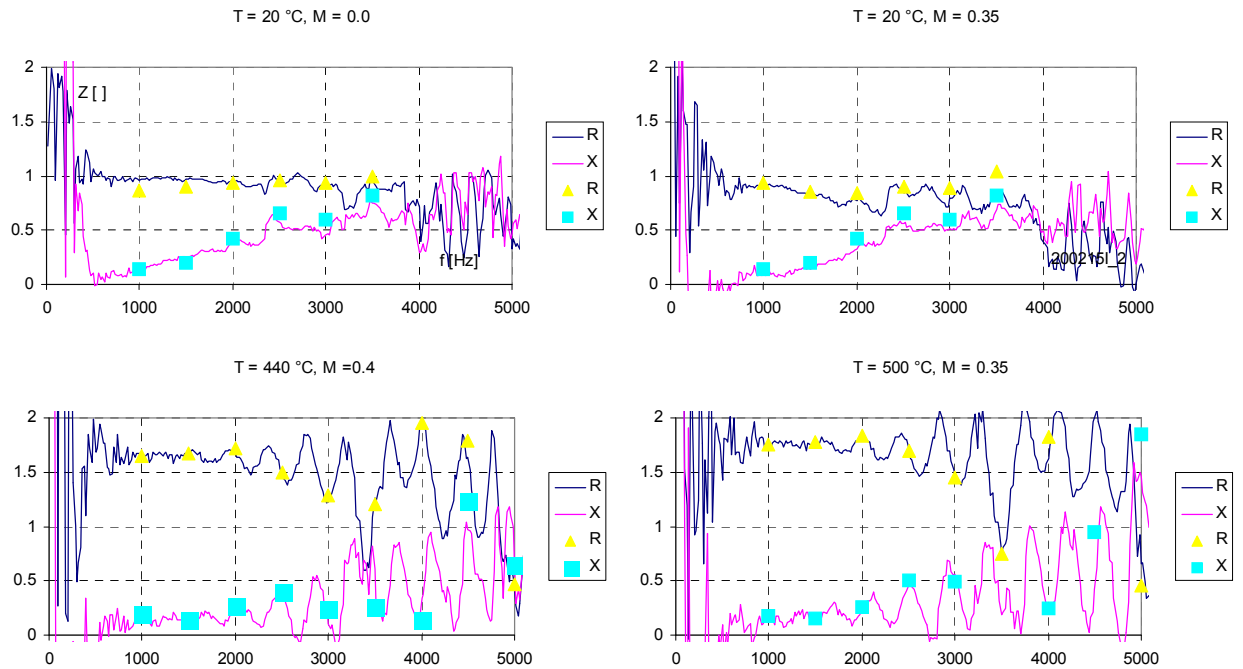
**Figure 4** Comparison between measured facing sheet impedance under periodic (left) and random (right) noise excitation, perforate liner,  $T = 500$  °C and  $M = 0.35$



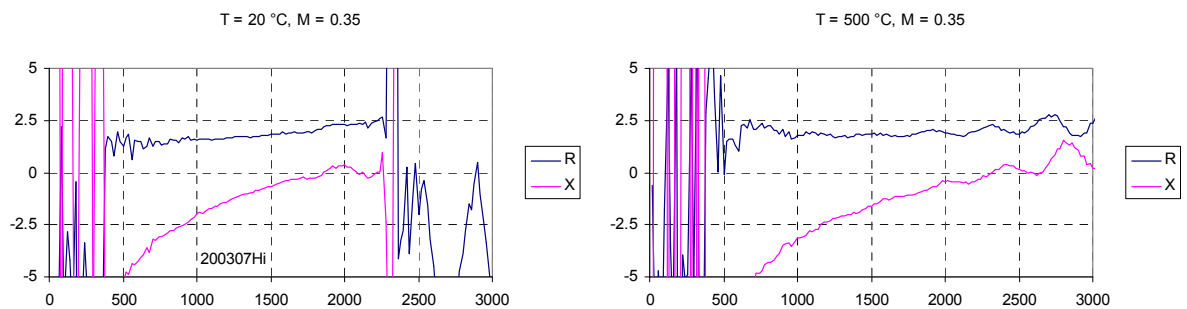
**Figure 5** Source spectrum with broadband random excitation (left) and acoustic signal to flow noise ratio as measured at the liner surface,  $T = 500$  °C,  $M = 0.35$ , OASPL = 135 dB



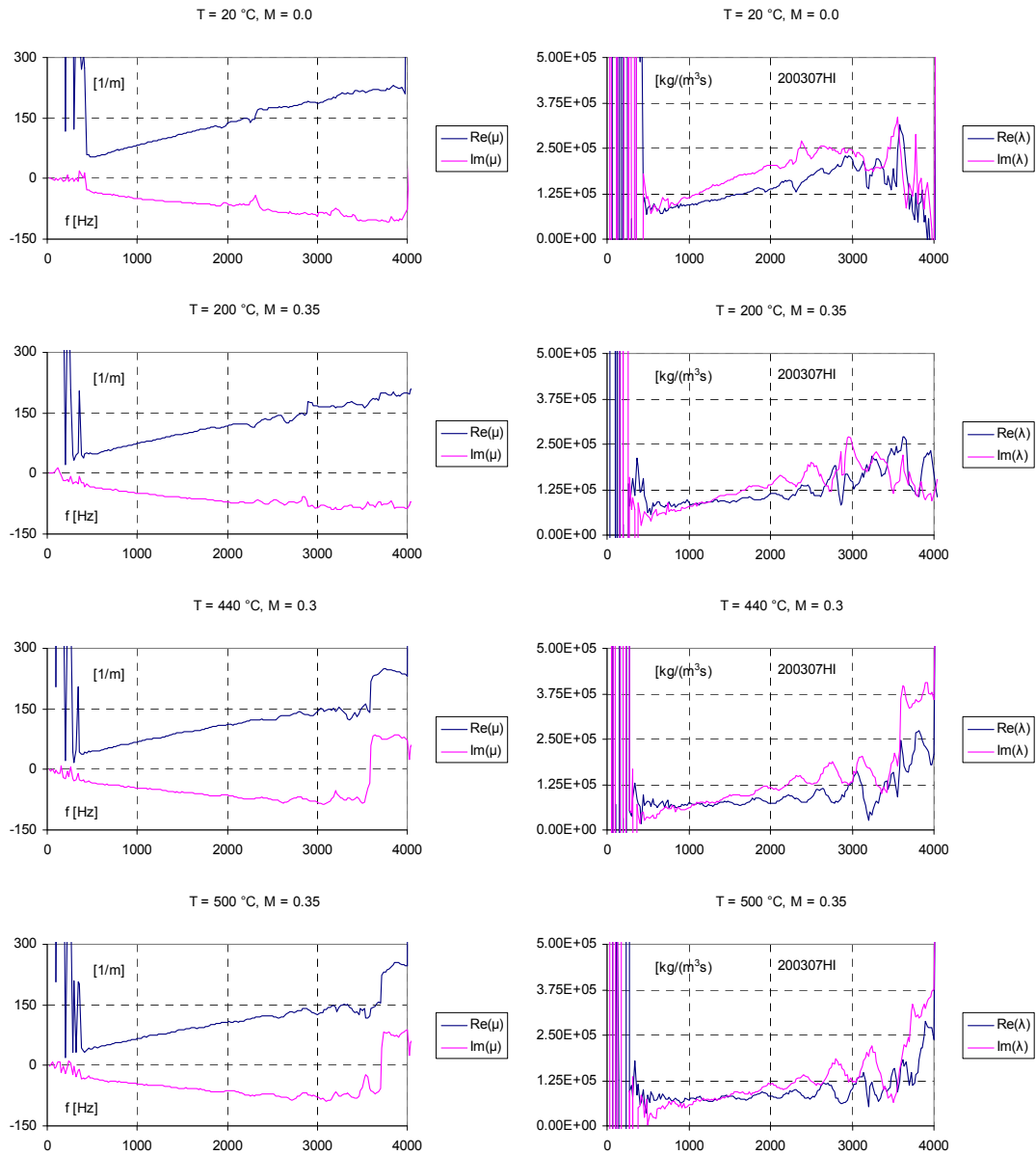
**Figure 6** In-situ acoustic impedance  $Z_f$  of the perforate facing sheet under broadband random and tonal excitations at four operating conditions at a maximum SPL of 140 dB



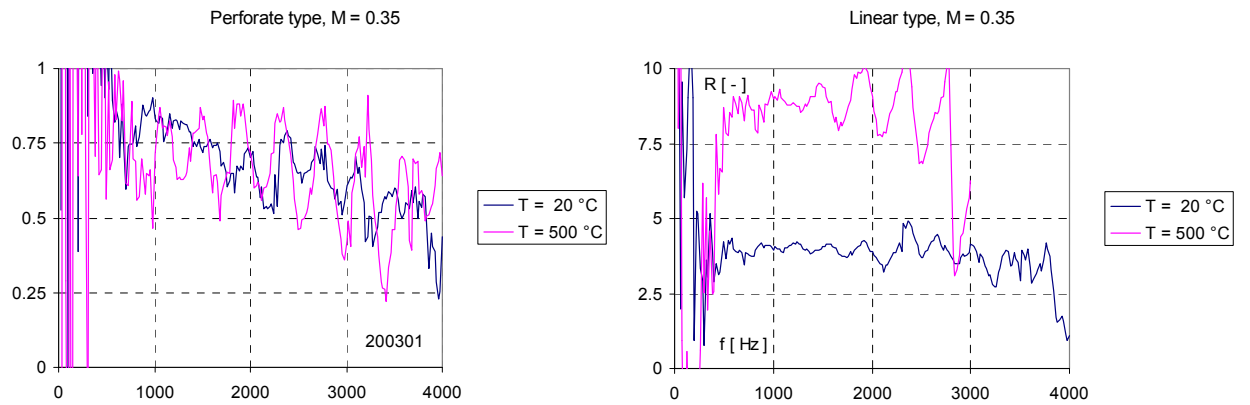
**Figure 7** In-situ acoustic impedance  $Z_f$  of the linear facing sheet under broadband random and tonal excitations at four operating conditions at a maximum SPL of 140 dB



**Figure 8** In-situ acoustic impedance of the porous liner  $Z$ , cavity half filled with porous material, flow Mach number is 0.35,  $T = 20^\circ\text{C}$  (left),  $T = 500^\circ\text{C}$  (right)



**Figure 9** Measured propagation constant  $\mu$  (left) and characteristic impedance  $\lambda$  (right) of porous liner as function of frequency at four operating conditions:  $T = 20^\circ\text{C}$  and  $M = 0.0$ ,  $T = 200^\circ\text{C}$  and  $M = 0.35$ ,  $T = 440^\circ\text{C}$  and  $M = 0.3$  and  $T = 500^\circ\text{C}$  and  $M = 0.35$



**Figure 10** Main result: a key difference between the temperature effect on the facing sheet resistance of perforate (left) and linear (right) liner types under grazing flow ( $M=0.35$ )